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An extrusion method of tube with spiral inner fins by utilizing generation of spiral outer fins/grooves

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This paper presents a new extrusion method for fabrication of a tube with spiral inner fins. The spiral fins are formed by utilizing the generation of spiral outer fins or grooves, which drive the metal to circumferentially move with twist deformation. The effect of the outer fins/grooves is examined for realizing the circumferential metal flow. The position of the mandrel has an ability to flexibly control the spiral angle. This method would drastically enhance the productivity and reduce the manufacturing cost, as the tube would be manufactured directly from a billet through only one process.

Metal forming; Extrusion; Tube

1. Introduction

Tubes with spiral inner fins, which are concisely called "spiral fin tubes" here, are one of the important and useful components in industry. The spiral fin tubes are used in chemical plants, electric devices and so on. The representative tubes are shown in Figs. 1(a) and (b). The tubes with large inner fins accelerate chemical reactions in the chemical industry, as the area of the tube inner surface is large. They are used in petroleum refineries, for example. The tubes with small inner fins enhance the heat change efficiency when they are mounted in air conditioners and refrigerators. The small fins enlarge the contact area between the tube material and the fluid inside, and affect the fluid flow for higher heat transfer [1].

The spiral fin tubes are conventionally manufactured by many forming processes. In the case of copper tubes, the tubes are manufactured by extrusion, pilger rolling, drawing and ball spin forming with a spiral plug inside the tube [2]. Some engineers proposed a new method that twists a tube, which is formed in ball spin forming with a straight plug inside [3]. In any case, a number of processes are needed, and it leads to the problem of low productivity and high manufacturing cost. In the case of cold forging, new processes have been developed for manufacturing helical solid parts with large teeth for gears [4].

The development trend of new extrusion processes could solve the problem. Conventional processes have the limit that the cross-section of the extruded tubes are completely uniform. New processes have started to break through the limit. A new extrusion method with a tapered mandrel can flexibly change the thickness in the longitudinal direction [5]. Another process is proposed for extending the flexibility over the length in the composite extrusion [6]. A new method by Takatsuji et al. succeeded in fabricating a spiral angle up to 7.5° using a rotatable plug in the extrusion [7]. Shiraishi et al. proposed an extrusion method for spiral fin tubes with a complicated mechanism using a clay billet [8]. However, the method is too complex to realise for metal billets. Khalifa et al. developed a new process called helical profile extrusion (HPE), which could fabricate a solid bar with three large protrusions [9].

This paper presents a new extrusion method for fabrication of spiral fin tubes. The method utilizes the generation of spiral outer fins or grooves, which drive the metal to circumferentially move. Schematic illustrations of the tubes are shown in Figs. 1(c) and (d). The tube with outer fins would be used in commercial refrigeration and air conditioning equipment that need high heat change efficiency. The tubes with outer grooves would be used in air conditioners, where the tubes are connected with flat sheet metals and outer fins should not exist. Moreover, the possibility of flexible control of the spiral angle is also examined as shown in Fig. 1(e). The proposed extrusion method would drastically enhance the productivity and reduce the manufacturing cost, as the spiral fin tube would be manufactured directly from a billet through only one process.

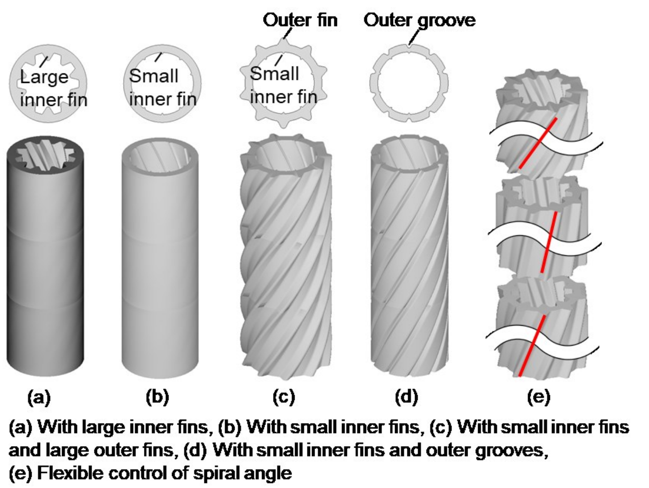


Figure 1. Tubes with inner fins

2. New extrusion method and fundamental mechanism

2.1. Extrusion method using a die with grooves/fins

Fig. 2 shows schematic illustrations for extrusion set-up and tools, and Fig. 3 shows the tool geometries. The unique point of the proposed method is that the die has spiral grooves/fins for generation of fins/grooves on the outer surface of the tube just as the mandrel has spiral grooves for fabrication of spiral fins on the tube inner surface. If the mandrel grooves were large enough, the mandrel grooves would twist the tube to some extent without the help of the spiral grooves/fins on the die. This phenomenon without the die grooves/fins is confirmed by the authors' previous research [10]. However, the fabrication of small fins is also needed in industry, and then a more effective extrusion method is demanded. In order to meet the demand, this paper proposes a new method which adds the die grooves/fins for twisting the tube by generating outer fins/grooves.

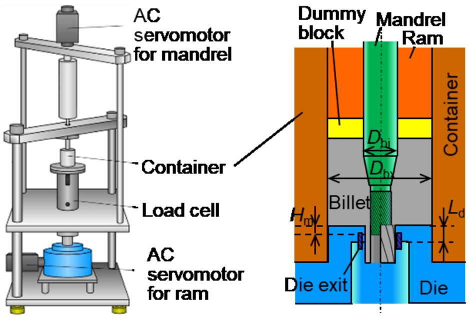
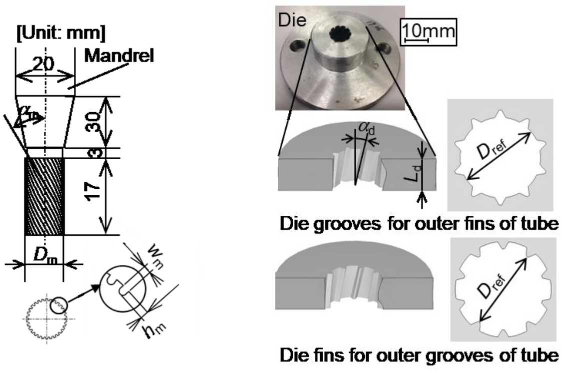


Figure 2. Composition of experimental set-up and tools



(a) Mandrel (b) Die

Figure 3. Tool geometries

Table 1 Standard extrusion condition

Billet	Material	Special pure lead (Pb>99.99 mass%)
	Outer diameter D_{bx}/mm	35
	Inner diameter D_{bi}/mm	20
	Initial length L_b/mm	55
Die	Number of grooves N_d	10
	Spiral angle α_d/°	30
	Diameter D_{ref}/mm	11
	Groove/fin shape	Triangle
		Trapezoid
	Groove/fin width w_d/mm	0.58 - 1.15
	Groove/fin height h_d/mm	0.25 - 1.0
	Bearing length L_d/mm	8
Mandrel	Number of grooves N_m	30
	Diameter D_m/mm	8.8
	Spiral angle α_m/°	30
	Groove shape w_m x h_m / mm	Semicircle 0.25 x 0.1
	Mandrel-tip position H_m/mm	Equal to L_d (=8mm)
Others	Ram velocity v_r / mm·s^{-1}	0.1
	Extrusion ratio R_{ex}	9.8 – 18.6 (depending on fin/groove size)

Table 1 shows the standard extrusion condition in this paper. Lead billets were used, as lead is a representative material for simulating hot extrusion or other hot forming of metals. The mandrel position H_m was set to be equal to the die bearing length L_d.

The shapes of die grooves/fins are shown in Fig. 4. Three types of die grooves or fins were prepared. A trapezoid was used for examination of the mechanism of twisting metal flow.

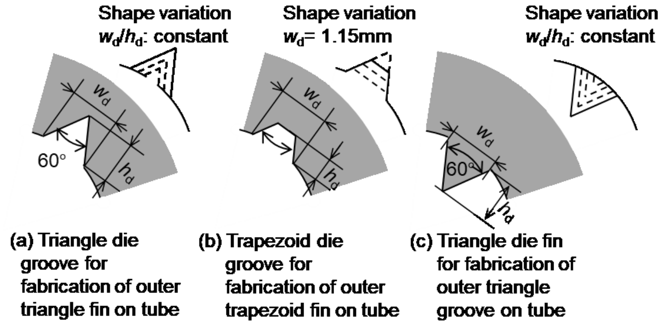


Figure 4. Shapes of die fins and grooves

2.2. Preliminary examination using the finite element method

The finite element method (FEM) was carried out for examination of the effect of the die groove for driving metal to flow in the circumferential way. Elastic-plastic analysis was carried out using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. A von Mises' yield criterion was adopted, and the normality principle was applied to the flow rule. Constraints were dealt with by the penalty function method. A dynamic explicit scheme and adaptive mesh were applied. 3-node triangle elements were employed.

The analysis was conducted in plane strain, which assumed longitudinal strain is zero. The inside surface of the material was constrained and the rotational displacement was given to the die as shown in Fig. 5. The model roughly estimates torque, which can be generated by different fin or groove geometries. In the actual extrusion, on the other hand, the tube is extruded between the constrained die and mandrel in 3-dimensional manner. However, the analysis qualitatively and relatively shows the roles of the die grooves and fins. The die groove/fin shapes are the same to those in Table 1. The material is assumed lead.

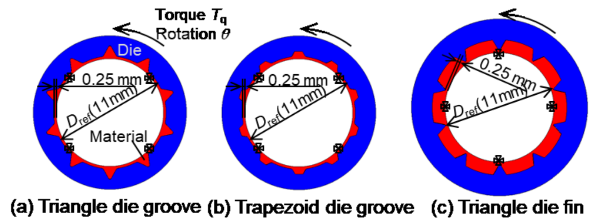


Figure 5. Dimension in FEM model for evaluating die groove/fin effect

Fig. 6 shows the relationship between rotation angle and torque, and the effect of die groove/fin shape on the relationship. Fig. 7 shows the magnified view of deformation under the conditions which are denoted by "a1"..."c4" in Fig. 6. The torque increases with increase of rotation angle. Torque increases with increase of die groove width w_d and height h_d for the triangle die groove as shown in Fig. 6(a). This would be attributed to increase of equivalent strain by shear deformation, which is observed at the root of the triangle fin in Fig. 7(a). The length of deformation zone L_s increases according to the groove size, resulting in higher torque.

It is noteworthy that the deformation of the trapezoid fin at w_d =1.15 mm and h_d = 0.25 mm (Fig. 7[b3]) is similar to that of the triangle fin at w_d =1.15 mm and h_d = 1.0 mm (Fig. 7[a1]). Therefore, the root part has an important role for increasing torque. However, when h_d is too small at 0.125 mm (Fig. 7[b4]), the deformation concentrates at one side of the root <P>, resulting in decrease of torque as shown by "b4" in Fig. 6(b).

The die fin has capacity of generating stronger torque than the die groove as shown in Fig. 6(c). The shear deformation appears at the inside surface of the material as the die fin strongly holds the material. However, when the height h_d is too small at 0.25 mm, a gap appears (Fig. 7[c4]), resulting in decrease of torque as shown by "c4" in Fig. 6(c).

That is to say that the triangle die groove has an ability of generating torque and the root of the triangle has the main role. Therefore, the trapezoid shape has also the same ability if it has a certain height h_d.

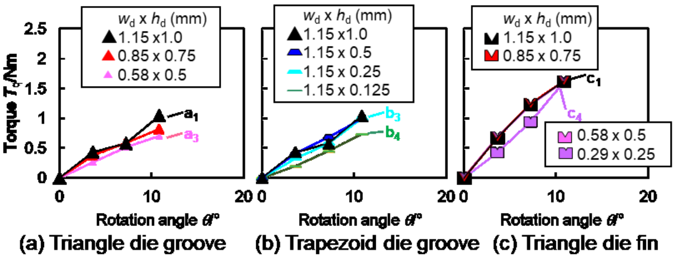


Figure 6. Effect of die groove/fin shape on relationship between torque and rotation angle (material: lead)

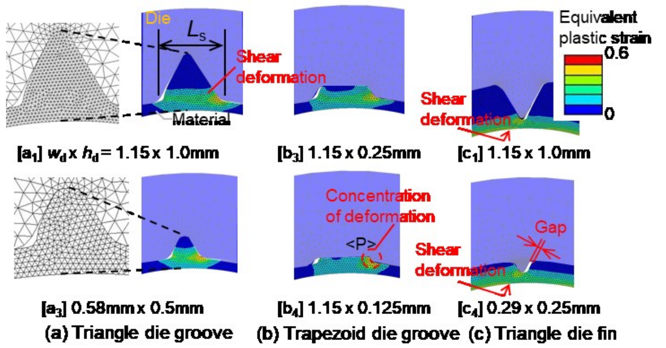


Figure 7. Deformation during die rotation (lead)

3. Experimental results

3.1. Generation of fins on tube by die grooves

Fig. 8 shows the experimental results of extrusion using the die with grooves under the conditions in Table 1. The symbols "H, h, m, l, f" denote the formed spiral angle γ or fin state. Fig. 8(b) shows the schematics of the shapes of the outer tube fins according to the shapes of the die grooves. The appearance of the tube fins are shown in Fig. 9. In Fig.8(a), the spiral angle increased with increase of the die groove width w_d in the case of triangle grooves as in [A3] -> [A1]. This would be attributed to the increase of the length of the deformation zone L_s in Fig. 7. Flaking was observed on the inner surface when w_d was small as in [A2] in Fig.9 because of the discrepancy between actual spiral angle γ and the mandrel spiral angle α_m.

Judging from Fig. 8(a), the die groove height h_d could be reduced to 0.50 mm for achievement of γ = 29°, and to 0.25 mm for γ = 25° as in [A1] to [B2] or [B3] in the case of trapezoid groove width w_d=1.15 mm. Therefore, the primary parameter is w_d and it should be larger than 1.15mm for fabrication of spiral angle. The second parameter is h_d, and it should be large to some extent for preventing concentration of deformation, which was observed by "b4" in Fig. 7(b). The most suitable condition is w_d >1.15 mm and h_d >0.5mm, and the allowable condition would be w_d >1.15 mm and h_d >0.25mm.

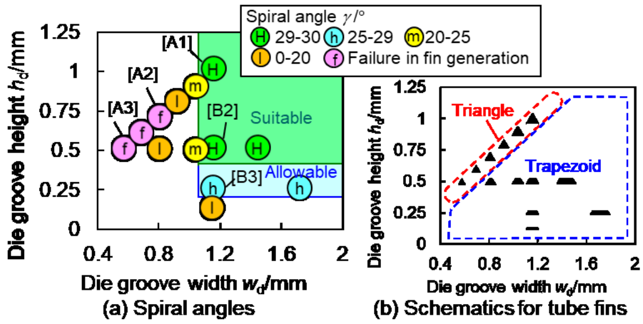


Figure 8. Process window by die groove shape (lead)

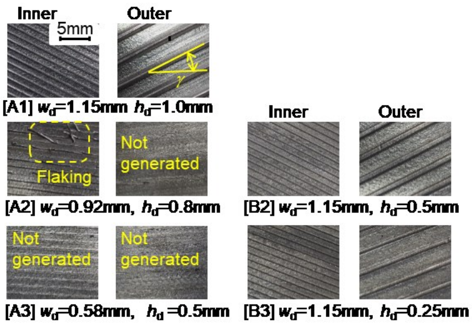


Figure 9. Formed inner and outer fins by proposed extrusion (lead)

3.2. Generation of grooves on tube by die fins

Fig. 10 shows the experimental results of extrusion using the die with fins under the conditions in Table 1. When the fin height h_d was larger than 0.5 mm, the spiral fin tube was successfully extruded with around the target angle of 30°. However, when h_d was smaller than 0.5 mm as in [C3], the spiral angle γ decreased. This would be attributed to the gap which was observed in [c4] in Fig. 7(c)

The cross-sections of the extruded tubes are shown in Fig. 11. When the die fin height h_d was large enough as in [C1], the formed outer groove was the shape of a triangle, which is the same as the shape of the die fin. On the other hand, when h_d was small as in [C3], wide grooves were observed, and the width was much larger than the one which was predicted by the FEM in [c4] in Fig. 7(c). It would be because the FEM was conducted assuming plane strain. The area cannot largely change under the condition of plane strain. However, the area can change in the actual extrusion as the metal can elongate in the longitudinal direction.

Fig. 12 shows the experimental results using aluminium alloy AA1100. Extrusion temperature was set at 600°C, which was slightly higher than that in industry due to load limitation of the machine. The spiral angle γ was 24°, which is less than the target of 30°, leading to smaller inner fin size than those of mandrel groove in Table 1. The lower formability of AA1100 would be attributed to friction condition [9] or temperature distribution as the metal would be rapidly cooled when it contacts with tools.

There are some improving methods for securing higher spiral angle and filling ratio of fins. Ultrasonic vibrations in the axial direction might increase the filling ratio. Rotating guide tools might help spiral movement as Selvaggio et al. proposed [11].

3.3. Flexible control of spiral angle by mandrel positioning

It might be possible to control the spiral angle of the extruded tube arbitrarily by positioning the tip of the mandrel H_m which is shown in Fig. 2. The tube wall comes through between the mandrel and the die bearing, and the tube will be twisted when the grooves/fins exist on the surface of the mandrel and the die bearing. Therefore, the spiral angle might decrease with decrease of the mandrel position H_m.

The feasibility was experimentally examined. Fig. 13 shows the effect of the mandrel position H_m on the spiral angle γ. The figure includes the extrusion conditions, which are different from those in Table 1. Larger die grooves were adopted, as small die grooves would lead to flaking of the inner fins on the tube surface, to which the similar phenomena was observed in Fig. 9 [A2] due to the discrepancy between the actual spiral angle and the mandrel spiral angle. Therefore, the extruded tube had large inner fins as shown in Fig. 1(e).

The spiral angle on the tube γ decreased with decrease of the mandrel position H_m as expected above. The bearing length L_d has little effect on the spiral angle γ. When H_m was 0 mm, the spiral angle γ became drastically small. The cross-sections of the extruded tubes are shown in Fig. 14. When H_m was 0 mm, the inner fins were not fabricated well. Therefore, H_m should be set equal to or larger than 2mm. As a result, it is revealed that the proposed method could successfully control the spiral angle γ between 17° and 30° by changing the mandrel position H_m between 2 and 14 mm.

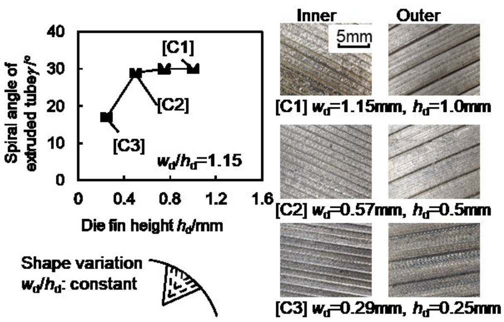


Figure 10. Effect of die fin size on spiral angle and fabrication of inner fins and outer grooves by proposed extrusion (lead)

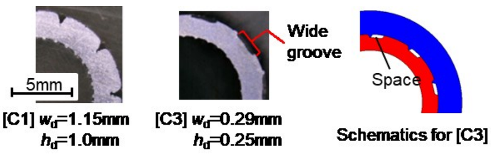


Figure 11. Cross-section of tube extruded by the proposed method (lead)

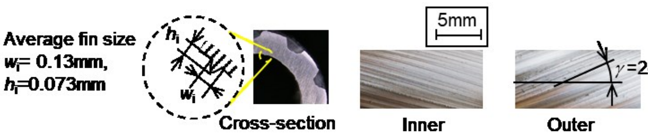


Figure 12. Shape of extruded aluminium alloy using die with fins (material: AA1100, die fin shape: [C1] w_d=1.15mm, h_d=1.0mm)

4. Conclusions

This paper presents a new extrusion method for fabrication of tubes with spiral inner fins, or "spiral fin tubes". The method would drastically enhance the productivity and reduce the manufacturing cost, as the spiral fin tube would be manufactured directly from a billet through only one process. The method utilizes the generation of spiral outer fins or grooves, which drive the metal to circumferentially move. Experimental results were mainly obtained using lead billets at room temperature.

When the die has grooves, the extruded tube has outer fins. The primary parameter for successful fabrication of spiral angle was the groove width, and the second parameter was die height. The suitable condition of these parameters was shown in the form of a process window.

When the die has fins, the extruded tube has inner grooves. When the die fin height was larger than a certain amount, the target spiral angle of 30° was achieved, which was seldom achieved by the previous extrusion methods of metals in the literature.

Moreover, the flexible control of the spiral angle was tried for fabrication of tubes with large inner fins and outer fins. The proposed method could successfully control the spiral angle between 17° and 30° by changing the mandrel position between 2 and 14 mm.

In the case of hot tube extrusion of aluminium alloy 1100, the spiral angle of 24° was achieved by the proposed method. Further improvements are needed for higher spiral angle.

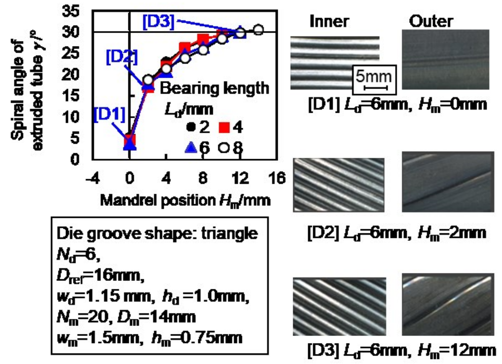


Figure 13. Flexible control of spiral angle by positioning mandrel (lead)

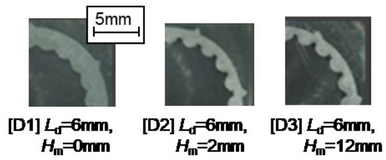


Figure 14. Effect of mandrel position on cross-section (lead)

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